# Introduction

Turing's automata theory and von Neumann's self-reproducing automata.

# Review

## Evolutionary Programming

## Genetic Algorithm

## Co-evolution

Selection pressure and co-evolutionary arms race. (Turner 95.)

## Artificial Life

### Cellular Automata:

# Adaptive coloration in Natural Organisms

# Mimicry

## History

Henry W. Bates first published in 1862 his findings about the similarities and dissimilarities between Heliconiinae and Ithomiinae butterflies, after 10 years of research in the Brazilian rain forest. For the next hundred years, it simulated heated discussion among all groups of people, scientists, philosophers, theologians, teachers and amateur naturalists. Bates collected ninety-four pieces of butterfly. He grouped them according to their similar appearance. He found butterflies having similar appearance, exhibiting morphological features which point to completely different species even families. Out of the ninety four species sixty seven are now classified as Ithomiinae, while twenty seven of them are Heliconiinae.

Bates was not only amazed with these finding, he was also determined to find an explanation for it. He found that Heloconiids were extremely abundant and very conspicuously coloured. They also had slow mobility so easier to catch. He noted,

‘*Although they fly slowly and are fragile in construction and apparently have no means of defence, they occur in areas where insectivorous birds hunt in flocks.*’

But these butterflies are not killed by birds, so an assumption is made that these butterflies are unpalatable and any palatable butterfly species which has the capability of having similar appearance will succeed in surviving insectivorous birds. This also provoked the idea that some Pierids pretend to be Heliconiids and thus enjoy protection which is really deserved only by the unappetising Heliconiids.

## Batesian Mimicry

Repulsive animals, such as heliconiids are very conspicuously coloured. Having this noticeable property, they are easily recalled by predators. Their wing pattern works as a warning to them. Once a predator has the knowledge of their inedible and unpalatable property, they would probably never attempt to try it again. As this is true, if any organism within close family and species, but being edible and having a deceptive resemblance to those conspicuously coloured species will be avoided by the predators. expresses,

"Such unpalatable appearing and yet edible animals thus possess a false warning pattern, they 'act a part'. An actor is a mime, and so the representation of a false warning pattern was called mimicry. Since Bates was the first to point out this phenomenon, it has received the name *Batesian Mimicry* in his honour."

In general, the animal which is avoided by predator for unpalatable behaviour is called the **model** and the imitating animal is called the **mimic**.

An important concept in contained in the self-evident term ‘pattern’, or more exactly, warning pattern, camouflage pattern and protective pattern. Man orients himself mainly with his eyes and he therefore pays particular attention to visual stimuli. But many animals orient predominantly by smell also our previous discussion of colouration and morphological characters applies equally well to odurs (olfactory stimuli).

## Mullerian Mimicry

Bates was not able to explain some phenomenon of mimicry. Occasionally two inedible unrelated butterfly species are amazingly similar in appearance. An explanation for this was provided by Fritz Muller in 1878. When there are multiple inedible species it is hard for predators to recognize each of them to know which one to consume and which one to avoid. Because of predator's limited memory, all these species still lose their number even after being inedible. So to save this loss, and to prevent more sacrifice of their own kind, inedible species from different family also tend to evolve to have similar appearance. This phenomenon is referred to as Mullerian Mimicry in the name of Fritz Muller.

## Evolution of Mimicry

## Formation of Mimicry Rings

The set of morphologically different species having similar appearance is considered within a single mimicry ring. This ring constantly evolves. One reason being predators have limited memory, and also newly born predators take certain time for learning.

In discussing the formation of mimicry rings, makes an analogy to the way planets form.

"Like planets forming from a cloud of gas, clusters of mimetic species will arise, and form what we call mimicry 'rings'. Species occupying spaces in between the rings will be pulled into them, but sooner or later these focal patterns, having absorbed all the available species, will stabilize. If they differ too much from each other they will not be able to converge, for predators like birds will never mistake one for the other."

Regarding the dynamics of mimicry, discusses three different theories. Firstly, according to , and , evolution of rings happens in a slow gradual continual process. Secondly, and suggests that mimics are created in a single, final mutational step. Thirdly, a synthetic theory also called *two stage model* has been proposed, which originated by and . According to this theory, in the first step mimics get a very close resemblance to the model, which gets more accurate over time, having a more refined resemblance.

# Modeling the evolution of mimicry

## Past work

Various models of mimicry has been simulated and explored. The model by (Turner & Speed, Learning and Memory in Mimicry. I. Simulations of Laboratory Experiments, 1996) and the mathematical model of (Huheey, 1988) tend to focus on the selective pressure on prey brought about by the particular learning abilities of the predator, and employ simple Monte Carlo or mathematical approaches.

(Sherratt, 2002) provides an innovative perspective on the evolution of warning signals by considering coevolving predator and prey populations. The model's predators are deterministic, in that they have a fixed behavioural strategy over their lifetime, and cannot learn from experience. For both cryptic and conspicuous prey, each predator has fixed policy of either attacking or avoiding.

The latest work on modelling evolution of Warning Signals and Mimicry with Individual based simulation is done by Frank and Noble. Their initial work at (Franks & Noble, Conditions for the evolution of mimicry, 2002) seems of focus on putting some conditions of mimetic evolution in an individual based model with multiple species preyed upon by a single abstract predator, where the appearance of each prey species can evolve but their palatability is fixed.

On (Franks & Noble, The origins of mimicry rings, 2003) a new model for the origin of Mimicry ring has been proposed. Accordingly theory suggests that all Mullerian mimics in an ecosystem should converge into one large ring, while this convergence will be encouraged by presence of Batesian mimics. So an evolutionary simulation to observe the above mentioned phenomenon has been presented in this piece of work.

Frank & Noble continue to test the influence on mimicry ring evolution by Batesian mimics in their work on (Franks & Noble, Batesian mimics influence mimicry ring evolution, 2004). Usually mathematical models of mimicry has fixed prey coloration and appearances, which enables a comparison of predation rates to demonstrate the level of protection a mimic might be afforded. In this model prey colorations are free to evolve. This phenomenon is used to examine the effect of Batesian mimicry on Mullerian mimics and mimicry rings.

### Sherratt's Model:

In this model the predators are deterministic, in that they have a fixed behavioural strategy over their lifetime, and cannot learn from experience.

### Models by Frank and Noble:

The first work by Frank and Noble is presented in (Franks & Noble, Conditions for the evolution of mimicry, 2002). In this model "multiple species are preyed upon by a single abstract predator; the appearance of each prey species can evolve but their palatability is fixed."

**Franks and Noble: The Origins of Mimicry ring**

Intro: The model is based on two working hypothesis:

1. All of the Mullerian mimics in a given ecosystem should eventually converge into one large ring in order to gain maximum protection.

2. If the Mullerian mimics do not converge into one large ring, then the presence of Batesian mimics could entice them to do so, by influencing the rings to converge.

Although there are many mathematical and stochastic models of mimicry in the biological literature, this model gives attention to the evolution of mimicry ring phenomenon from an artificial life perspective.

Model description:

The model contains a population of prey species each having an appearance and palatability level. Different species of prey were each assigned a fixed palatability level on a scale between zero and one (least to most palatable), where 0.5 is neutrally palatable. Palatable species have values greater than 0.5, and unpalatable species have values lower than 0.5. Each prey species has used two genes with values compositely representing their external appearance or phenotype. Both of these genes were constrained to values from 1 - 200. The Euclidean distance of one phenotype from another represented their level of similarity.

Similar to (Turner, Kearney, & Exton, Mimicry and the Monte Carlo predator: the palatability spectrum and the origins of mimicry, 1984)'s stochastic model, predators were modeled with a Monte Carlo reinforcement learning system. The predator's experience of each phenotype was represented by an attack probability, which was initialized to ambivalence at 0.5. After eating prey of a particular phenotype, the predator would make a post-attack update of the relevant probability according to the palatability of the prey consumed. The predator would use its experience of different prey appearances to help it decide on whether or not to attack then at the next opportunity.

Results:

## FormAL Framework

The FormAL framework is a collection of ideas and concepts taken from and are used to build a framework for modelling the evolution of mimicry. The framework consists of 3-D visual environment where agents of the individual based simulation gets complete freedom of movement following a certain pattern. Details of the individual components are explained in the following.

### Spatial representation of the environment

### 3D Visualization

### Agents

### Mobility

## Mimic and Model

### Pattern representation by Cellular Automata

### Species diversity

Hamming distance between different CA patterns have been used to distinguish between species.

Franks and Noble have used different models to diversify species. In (Franks & Noble, Conditions for the evolution of mimicry, 2002) they have used linear difference in number "constrained to a 'ring' of values from 1-20 (where 20 and 1 are neighbours)" to distinguish species diversity. Here the distance of one phenotype from another represents their level of similarity.

### Genetic representation of palatability

The palatability of each prey species is fixed and has been represented with 2 bit of the genome giving it a range of 0 to 3 with four levels of palatability. The combinations are as follows:

|  |  |
| --- | --- |
| **Gene (Index 8 to 9)** | **Palatable** |
| 00 | True |
| 01 | True |
| 10 | False |
| 11 | False |

This representation is unlike (Franks & Noble, The origins of mimicry rings, 2003) where palatability level has been used on a scale between zero and one (least to most palatable), where 0.5 is neutrally palatable.

### Interaction between Mimics and Models

### Interaction with predators

## Predator

Predators in the simulation

### Learning

#### Hebbian Learning

#### Hopfield Network

### Design of Memory with Hopfield Network

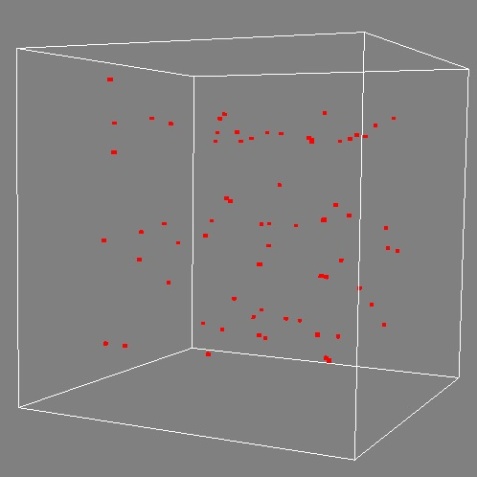
Predators have fallible sensory systems and the generalize from their predation experiences. Thus although they are much more likely to mistake a perfect mimic for its model, they can still mistake approximate resemblances for the real thing.

### Genetic representation of mobility and reproduction capability

Each predator in the simulation has a genetic representation. The genome of the predator is represented with a 5 bits binary value.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Mobility | | | | Reproduction Capability |
| 1 | 0 | 1 | 0 | 1 |

Movement behavior of a Predator calculated from its Genome. The first 4 bits of the genome of this species are converted from binary to decimal to determine the magnitude of force at which it will move towards the maximum crowd of Prey present within its neighbourhood. So mobility of a predator varies within a range of 0-15 units. If no prey is present in the nieghbourhood then this force is active in trying to keep predators distributed all over the cells. A predator chooses the neighbourhood cell which contains the least number of predators. When the neighbourhood contains zero predators, it would select any one of them randomly and move towards that cell.



The above screenshot is from the simulation with only 40 predator species. It is presented to show the behavior of predator species in the simulation in absence of any prey species. As it can be observed the predator are distributed all over the cells with a constant mobile behavior to switch to another neighbouring cell depending on which ever contains the least number of predator and also most number of prey species. This behavior of predator has been desined to enforce the predatory behavior of this species and also to have increase predator prey interaction in the simulation in terms of one species chasing the other for search of food.

The fifth gene of the predator is used to represent their capability of reproduction. Depending on its binary value a predator in the simulation will or will not be able to reproduce in the simulation.

### Reproduction process

The reproduction process for predators is similar to prey species. As the learning capability of predators do not have any genetic representation, only the mobility behaviour and reproduction capability behaviour takes effect in the reproductive process of predator species from one generation to another.

There are two control parameters that effect reproduction of predator species in the simulation. The first is the "Reproduction Age Limit". This the minimum age a predator has to reach before starting to involve itself for reproduction. This parameter has been set to 500 iterations during the result and analysis section of the thesis. The second parameter is "Reproduction Interval" which has been varied in the simulation from 1000 to 3000 iteration depending on the population of palatability of the prey species. This is a very important parameter for the simulation as it determines the overall predator population and its rate of increment. Depending on this value we can control the rate of predation on prey species, which on the other hand controls the rate of mimetic behaviour of the overall prey population.

When the above two conditions are met, meaning the predator reaches it age for reproduction and also crosses every age interval, it randomly select another predator residing in the same cell. If this random predator is capable to reproduce depending on its 5th gene, then with a random single point crossover and mutation a new predator species in born which also resides on the same cell and initializes with zero memory configuration. Similarly when the new born predator reaches its maturity of reproductive age and if its capable to reproduce then the process iterates itself.

### Interaction with Models and Mimics

# Results and Analysis

Experiment 1: Initial configuration of two prey species:

|  |  |  |  |
| --- | --- | --- | --- |
| **Prey configuration** | | | |
| Population (Cellular Automata) | Rule 110 (Palatable) | CARule110.jpg | 108 |
| Rule 30 (Unpalatable) | CARule30.jpg | 108 |
| Reproduction | Age Limit | 100 | |
| Interval | 1000 | |
| Mutation Rate | Pattern | 0.05 | |
| Genome | 0.5 | |
| Demise Age | 2000 | | |
|

|  |  |  |
| --- | --- | --- |
| **Predator configuration** | | |
| Population | | 10 |
|
| Reproduction | Age Limit | 500 |
| Interval | 1000 |
| Mutation Rate | 0.3 | |
|
| Demise Age | 2500 | |
| Minimum Attack Age | 500 | |
| Memory Configuration | Minimum | 2 |
| Maximum | 10 |

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Prey configuration** | | | **Predator configuration** | |
| Population | Rule 110 (Palatable) | CARule110.jpg | 108 | 10 | |
| Rule 30  (Unpalatable) | CARule30.jpg | 108 |
| Reproduction | Age Limit | 100 | | 500 | |
| Interval | 1000 | | 1000 | |
| Mutation Rate | Pattern | 0.05 | | 0.3 | |
| Genome | 0.5 | |
| Demise Age | 2000 | | | 2500 | |
| Minimum Attack Age |  | | | 500 | |
| Memory Configuration |  | | | Minimum | 2 |
| Maximum | 10 |

The above set of parameters were carefully selected to be the initial condition for this run of the simulation. This test has been done with two sets of prey species with very different CA pattern and with opposite palatability and equal population. To control reproduction of the prey species their age limit has been set to 100 iterations into the time the species were alive. And the reproduction interval was set to 1000 iterations.

Pattern mutation rate has been set to a minimal level of 0.05 as by increasing this variable it is possible to increase the size of the number of mimicry rings present in the simulation. The Genome mutation rate controls the rate at which genome of the child prey species will deviate from their parents. As mentioned earlier the genome mutation rate has been separated from the pattern mutation rate to bring more control to the number of mimicry rings generated.

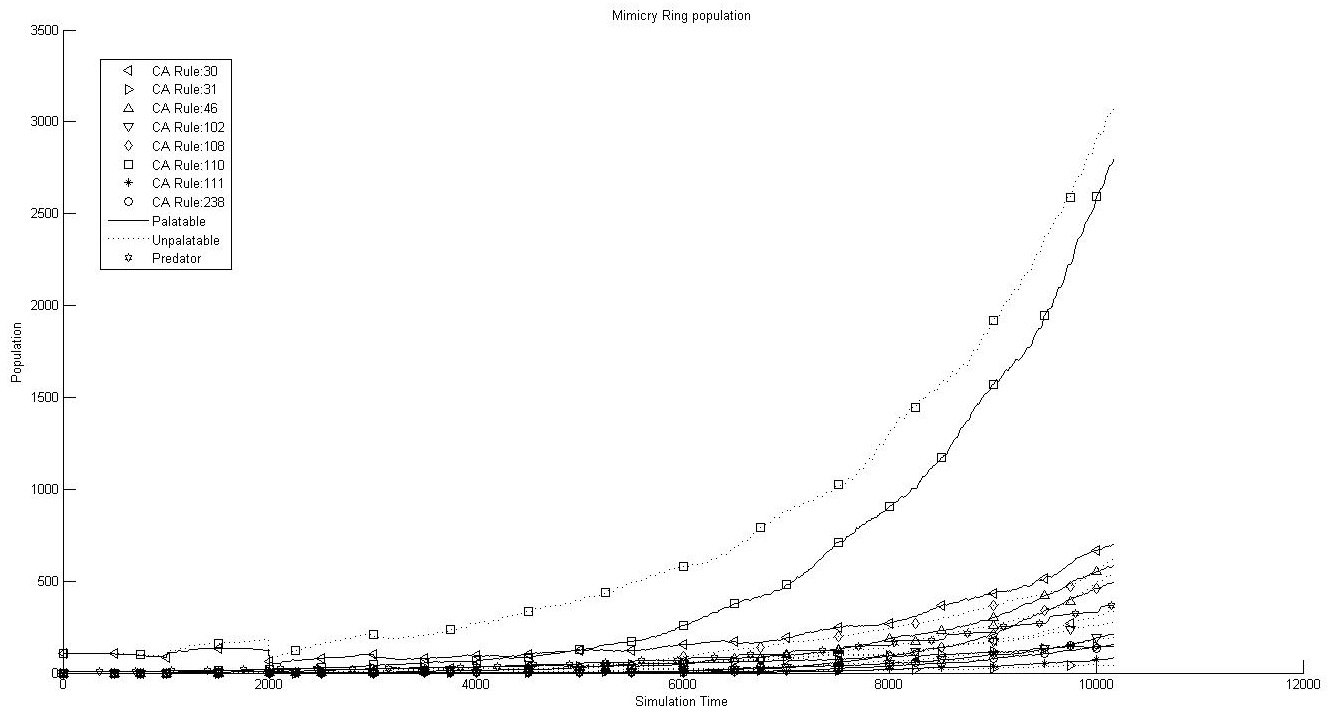
Prey demise age has been kept to 2000 iterations while predator demise age is set to 2500. But later in the following results predator demise age has been increased to 5000 iterations. Predators in this simulation generates selection pressure for the evolution of mimicry. So the longer a predator is present in the simulation it will be making intelligent decisions in term of selecting which prey species to consume and which one to avoid. But with the current rate of demise for predator we were able to create successful mimetic population of prey species as we will see in the analysis in the following results.

Initial population of predator species has been set to 10 which is in accordance with the prey population in the simulation. The reason for such low number of predator is, unlike prey species which are consumed by predators, there is no cause for the predator species to die accept their natural cause of death, that is to reach their demise age. So predator population can explode very easily. That is why their population is controlled in a restrictive manner with the help of high reproduction age limit and reproduction age interval.

The memory configuration size for predators are a very interesting parameter. The minimum memory size is directly associated with the number of prey species with which we initiate the simulation. Otherwise evolution of mimicry is not observed. As mentioned earlier the minimum memory size is the number of prey species predator would consume before starting to make decisive consumption of prey species. After the initial birth of a predator and when the minimum attack age is crossed, it starts consuming prey species present in its vicinity without making any judgement. At this point its memory size is zero. As long as the minimum memory size is not reached predators will blindly consume prey species and insert their CA pattern and associated palatability into its Hopfield memory bank. No later than the minimum memory size has been reached, predators will start making intelligent decision about consuming its prey species. When catching a prey if its memory tells that it is palatable, it will consume that prey. Otherwise if memory recognizes it to be unpalatable predator will certainly let it go.

Now as we know the behaviour of Hopfield memory, a recognition result will always be achieved depending on the similarity of the patterns stored in memory. So when minimum memory size has been reached the predator will always make a decision based on the similarity of the prey pattern previously captured and the patterns stored in memory.

Simulation time: **10000 and above**



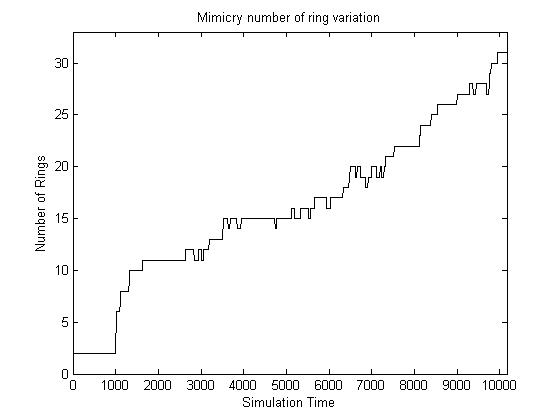
The above plot is simulation time verses prey population after running it for above 10000 iterations. With the initial configuration in the above table we can observe that multiple rings of prey population has been created. Two prey species are in a ring if their CA pattern have a hamming distance within 10 bits. Population of palatable species has been represented with line curve while population of unpalatable species has been presented with dotted curve. Different signs of squares, triangles and diamonds have been used to distinguish between species of prey population. The simulation was initiated with two prey species having CA rule of 30 and 110 and being palatable and unpalatable consecutively.

By closely observing the graph we could see the population of two species have started dropping at around time 500 when the initial predator population reaches this maturity for consuming prey species. At around time 1000 the prey population starts reproducing as the population increases. At around the same time different other species of prey population gets to be born with mutated CA patterns. Over time the population of CA Rule 110 dominates the population as most predators recognizes it as unpalatable. And similarly a population of CA Rule 110 or within the same ring of palatable species starts rising, while at one point overlaps the population of CA Rule 30 (Time: 5000 approx.) which was initially considered as a set of palatable species.

We can observe from the above results that the evolution of mimicry has taken effect. A population of mimics were successfully able to exceed the population of other prey species the reason being avoidance by predators of prey pattern similar to unpalatable ones. We can conclude that Batesian mimicry has taken effect in the simulation.

The above configuration is also the most appropriate condition for Mullerian Mimicry. We can observe that a single pattern of unpalatable species dominate the entire population. These effects can be observed in this configuration where we can see the continuous increment of prey and predator population and eventually behaviours of Mullerian mimicry, where all prey species converge to a single ring of CA pattern.

Number of rings:

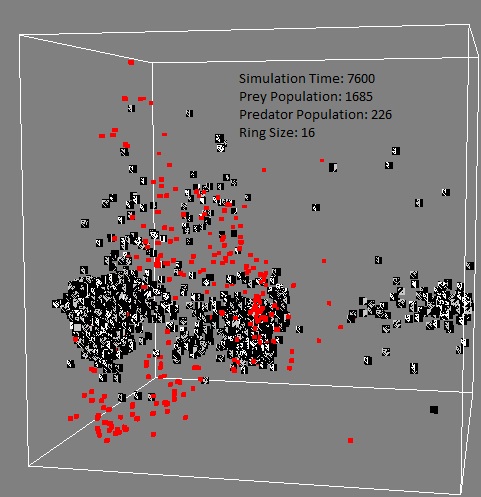


The number of rings in this simulation makes a slow increase from 2 at the initial configuration to 33 rings at the end of 10000 iterations. We can observe that a small change in CA genetic representation can have a very large effect in terms of the phenotype of the pattern with which the prey is represented. For example if we observe the following set of patterns genotype with very different phenotype:

|  |  |  |  |
| --- | --- | --- | --- |
| **CA Rule** | 60 ≡ 00111100 | 61 ≡ 00111101 | 62 ≡ 00111110 |
| **Pattern** | CARule60.jpg | CARule61.jpg | CARule62.jpg |

All the above set of patterns have a genetic bit difference of 1. So by a single mutation there can be three different set of phenotype for a child organism from its parent. This is largely the reason for the increased number of Rings created in the simulation. Only the 8 most populous rings have presented in the graph above with population verses simulation time.

Simulation time: **7600 and onwards**



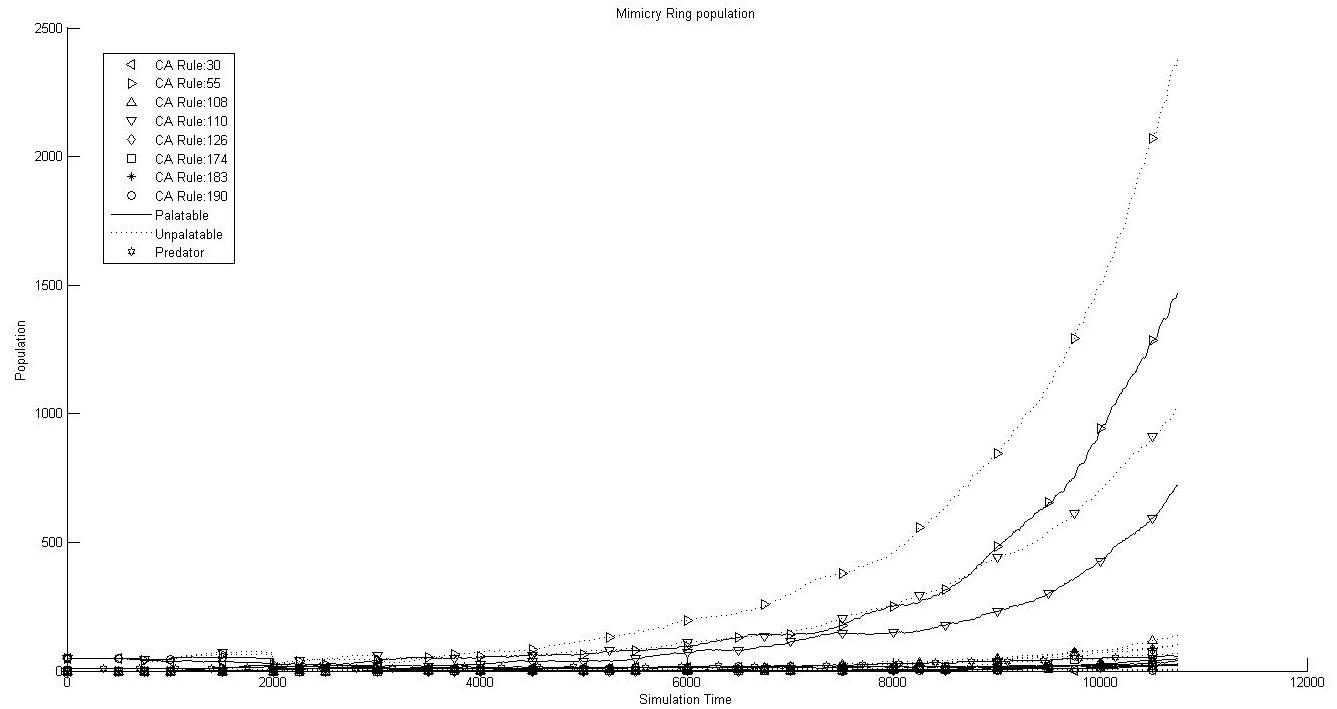
The above screen shot is for one instance of time of the simulation. The red agents are predators while the black agents with different textured patterns are the prey species. According to their behaviour most of the prey species are flocking together in a group while also being chased by the predators, whose sole purpose is to consume prey species.

Experiment 2: Initial configuration with four prey species:

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **Prey configuration** | | | **Predator configuration** | | |
| Population  (Cellular Automata) | Rule 110 (Unpalatable) | 50 | CARule110.jpg | Population | | 10 |
| Rule 30 (Palatable) | 50 | CARule30.jpg |
| Rule 55 (Unpalatable) | 50 | CARule55.jpg |
| Rule 190 (Palatable) | 50 | CARule190.jpg |
| Reproduction | Age Limit | 100 | | Reproduction | Age Limit | 500 |
| Interval | 1000 | | Interval | 1400 |
| Mutation Rate | Pattern | 0.05 | | Mutation Rate | 0.3 | |
| Genome | 0.5 | |
| Demise Age | 2000 | | | Demise Age | 2500 | |
|  |  |  | | Memory Configuration | Minimum | 4 |
|  |  |  | | Maximum | 10 |

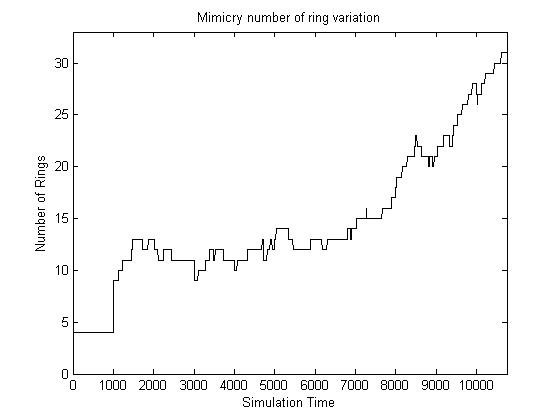
This run of the simulation has been initialized with four prey species with very different CA pattern configuration. The predator reproduction interval has been increased to 1400, while the minimum memory size has been increased to 4 instead of 2 as the predator is expected to memorize four different species of prey before starting to make intelligent decision about consuming them.

Simulation time: **10000 and onwards**

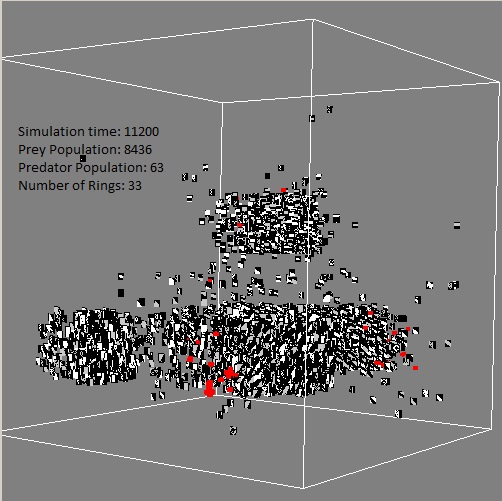


By observing the above graph we can see the two rings of unpalatable species which was put at the initial sate of the simulation has dominated after 10000 iterations. CA rule 55 has taken over all other species while CA 110 is following it (represented with dotted curve). Also the palatable prey species with similar patterns to CA rule 55 and 110 are taking full advantage of their deceiving pattern and increasing their population (represented with line curve). The two unpalatable set of patterns CA Rule 90 and 130 are unable to dominate the population. Different other mimicry rings are present in the simulation as we can observe from the graph of number of rings verses simulation time, the total number of rings reached somewhere near 33 while each of them has comparatively low representative population. Batesian mimicry is in full effect in this simulated environment.

Number of rings:



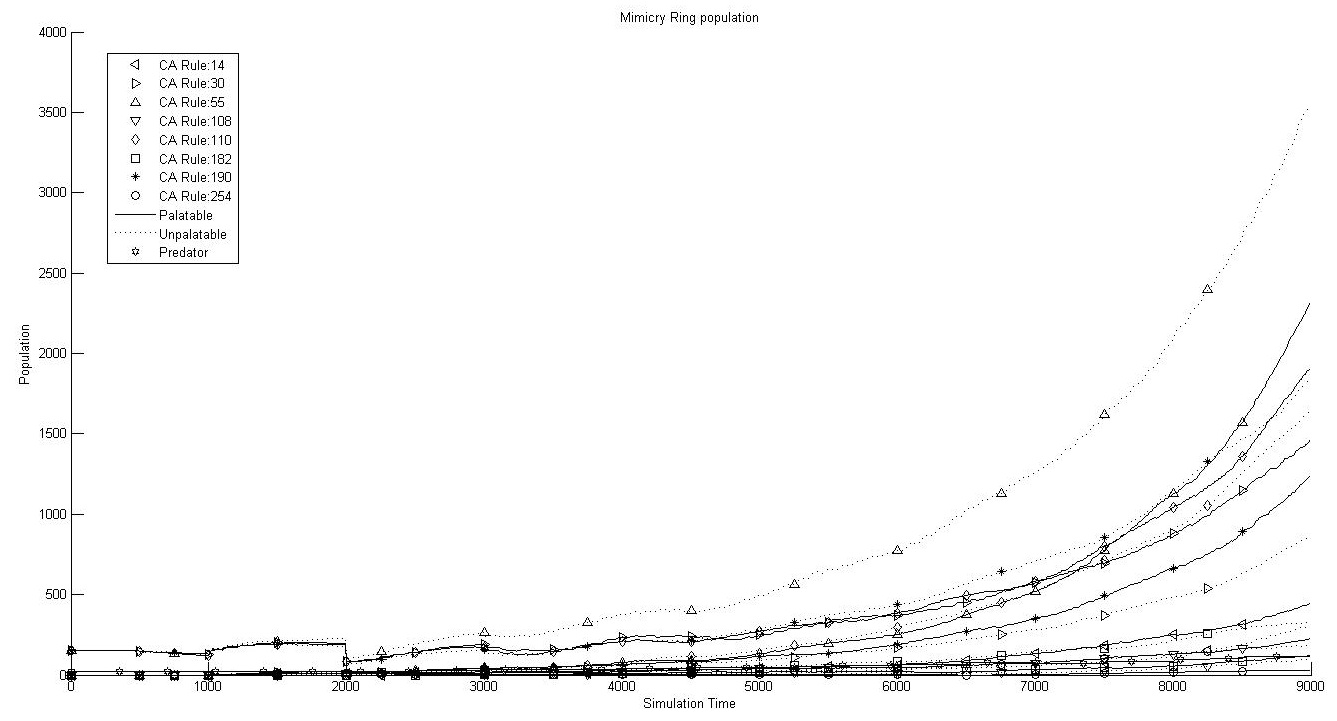
Simulation time: 11000 and onwards



Increased initial population with four prey species:

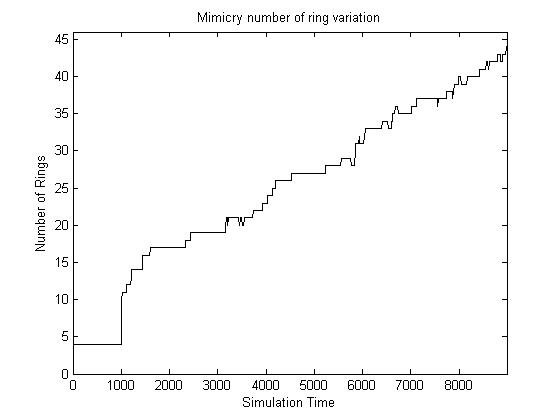
|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **Prey configuration** | | | **Predator configuration** | | |
| Population  (Cellular Automata) | Rule 110 (Palatable) | 150 | CARule110.jpg | Population | | 20 |
| Rule 30 (Palatable) | 150 | CARule30.jpg |
| Rule 55 (Unpalatable) | 150 | CARule55.jpg |
| Rule 190 (Unpalatable) | 150 | CARule190.jpg |
| Reproduction | Age Limit | 100 | | Reproduction | Age Limit | 500 |
| Interval | 1000 | | Interval | 2500 |
| Mutation Rate | Pattern | 0.05 | | Mutation Rate | 0.3 | |
| Genome | 0.5 | |
| Demise Age | 2000 | | | Demise Age | 7000 | |
|  |  |  | | Memory Configuration | Minimum | 4 |
|  |  |  | | Maximum | 10 |

In this run of the simulation some significant parameters have been updated. One is the initial population of prey species. It has been increased from 50 to 150 for each of the prey species increasing the overall population from 200 to 600. Secondly the number of predator population has been increased from 20 to 30. Thirdly, Predator demise age has been increased from 2500 to 7000 while their reproduction interval has been increased from 1400 to 2500. Increasing predator demise age can have an interesting effect, as the longer a predator is present in a simulation, the longer it will be making intelligent decision in terms of consuming its prey and there will increased selection pressure from the entire population of predators.



Some very interesting diversity of rings can be observed in the simulation for updating the parameters. The unpalatable rings and their deceptive counterparts(palatable prey with similar pattern) still have their dominance. We can observe CA Rule 55 and 190 are the highest number of population. Interestingly enough CA Rule 110 which started as a palatable prey species has also taken dominance in the population which is the second highest. Both palatable and unpalatable version of CA Rule 110 are present with equal population density.

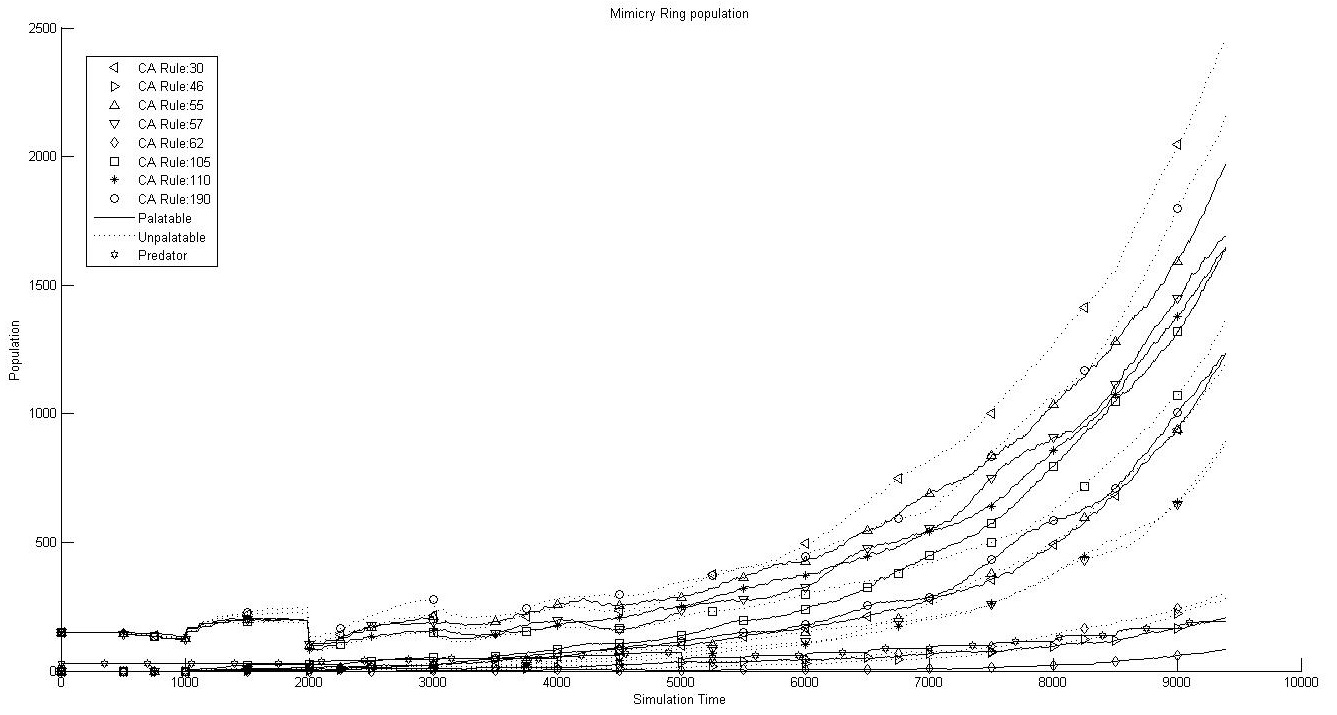
Number of rings:

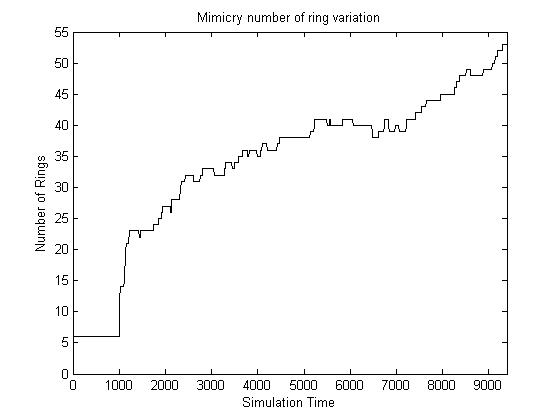


The total number of rings had much increment in this run compared to the previous one. To summarize we can observe increased diversity of prey population and much more interaction between predators and prey.

Increased initial population with six prey species:

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **Prey configuration** | | | **Predator configuration** | | |
| Population  (Cellular Automata) | Rule 110 (Palatable) | 150 | CARule110.jpg | Population | | 30 |
| Rule 30 (Unpalatable) | 150 | CARule30.jpg |
| Rule 55 (Palatable) | 150 | CARule55.jpg |
| Rule 190 (Unpalatable) | 150 | CARule190.jpg |
| Rule 57 (Palatable) | 150 | CARule57.jpg |
| Rule 105 (Unpalatable) | 150 | CARule105.jpg |
| Reproduction | Age Limit | 100 | | Reproduction | Age Limit | 500 |
| Interval | 1000 | | Interval | 2000 |
| Mutation Rate | Pattern | 0.05 | | Mutation Rate | 0.3 | |
| Genome | 0.5 | |
| Demise Age | 2000 | | | Demise Age | 5000 | |
|  |  |  | | Memory Configuration | Minimum | 6 |
|  |  |  | | Maximum | 10 |



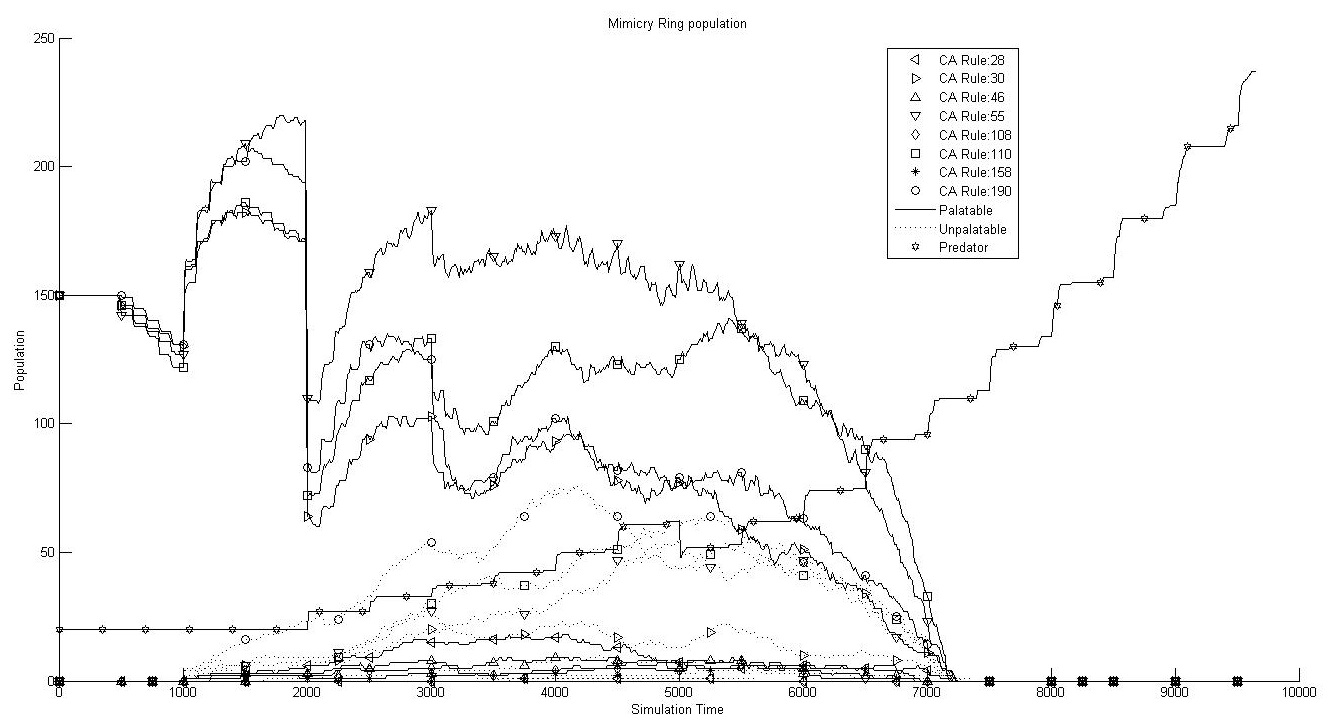


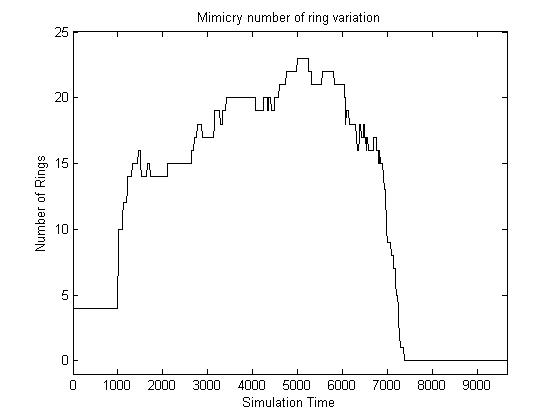
Initial configuration with more unpalatable than palatable species.

Initial configuration with more palatable than unpalatable species.

Initial configuration with only palatable species.

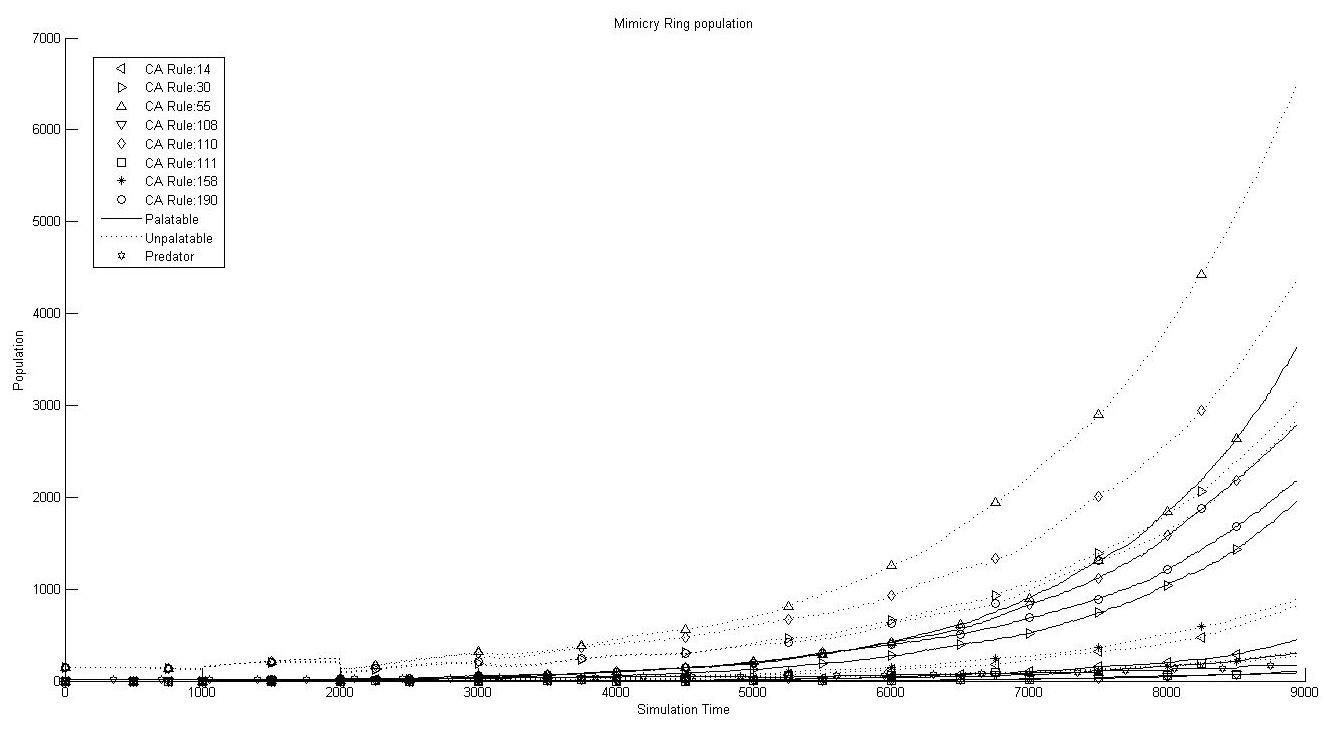
|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **Prey configuration** | | | **Predator configuration** | | |
| Population  (Cellular Automata) | Rule 110 (Palatable) | 150 | CARule110.jpg | Population | | 30 |
| Rule 30 (Palatable) | 150 | CARule30.jpg |
| Rule 55 (Palatable) | 150 | CARule55.jpg |
| Rule 190 (Palatable) | 150 | CARule190.jpg |
| Reproduction | Age Limit | 100 | | Reproduction | Age Limit | 500 |
| Interval | 1000 | | Interval | 2000 |
| Mutation Rate | Pattern | 0.05 | | Mutation Rate | 0.3 | |
| Genome | 0.5 | |
| Demise Age | 2000 | | | Demise Age | 5000 | |
|  |  |  | | Memory Configuration | Minimum | 4 |
|  |  |  | | Maximum | 10 |

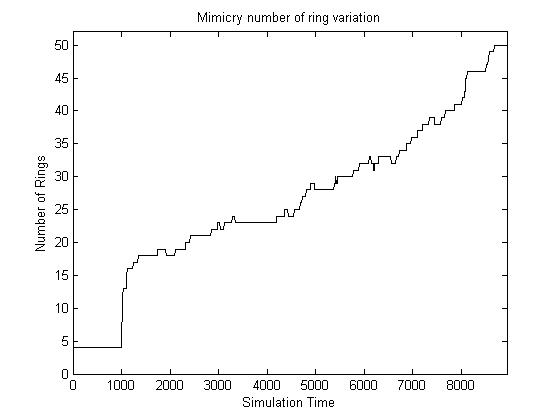




Initial configuration with only unpalatable species.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **Prey configuration** | | | **Predator configuration** | | |
| Population  (Cellular Automata) | Rule 110 (Unpalatable) | 150 | CARule110.jpg | Population | | 30 |
| Rule 30 (Unpalatable) | 150 | CARule30.jpg |
| Rule 55 (Unpalatable) | 150 | CARule55.jpg |
| Rule 190 (Unpalatable) | 150 | CARule190.jpg |
| Reproduction | Age Limit | 100 | | Reproduction | Age Limit | 500 |
| Interval | 1000 | | Interval | 2000 |
| Mutation Rate | Pattern | 0.05 | | Mutation Rate | 0.3 | |
| Genome | 0.5 | |
| Demise Age | 2000 | | | Demise Age | 5000 | |
|  |  |  | | Memory Configuration | Minimum | 4 |
|  |  |  | | Maximum | 10 |



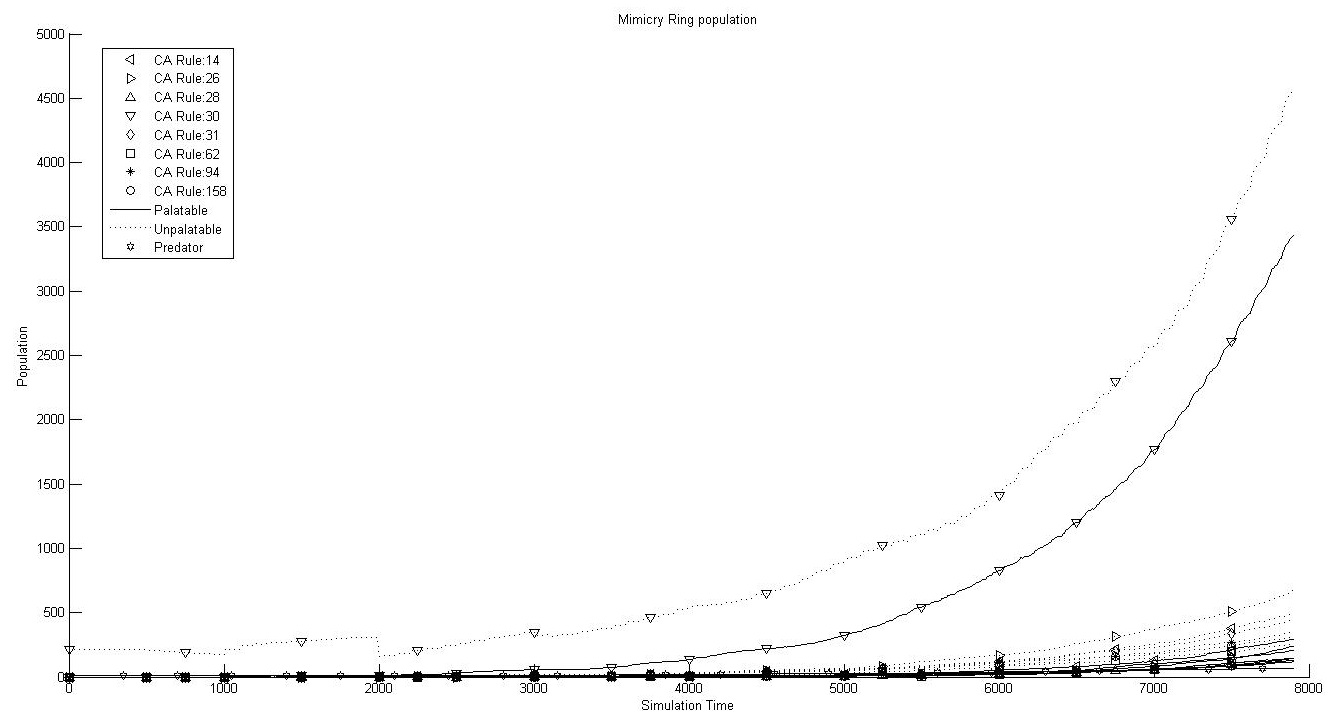


Initial configuration with different set of CA rules.

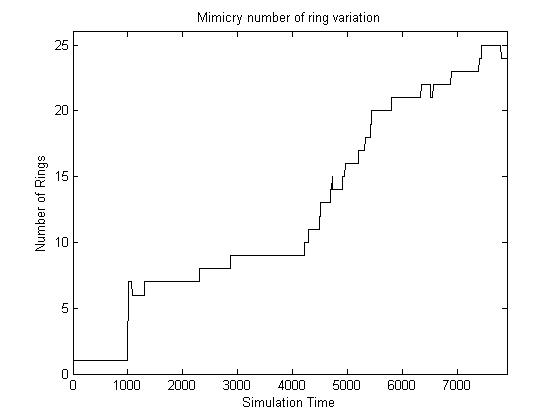
Initial configuration with only one CA rule or a single prey species.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  |  | **Prey configuration** | | **Predator configuration** | | |
| Population  (Cellular Automata) | Rule 30  (Unpalatable) | CARule30.jpg | 216 | Population | | 10 |
| Reproduction | Age Limit | 100 | | Reproduction | Age Limit | 500 |
| Interval | 1000 | | Interval | 2500 |
| Mutation Rate | Pattern | 0.05 | | Mutation Rate | 0.3 | |
| Genome | 0.5 | |
| Demise Age | 2000 | | | Demise Age | 7000 | |
| Minimum Attack Age | 500 | |
|  | | | | Memory Configuration | Minimum | 2 |
| Maximum | 10 |

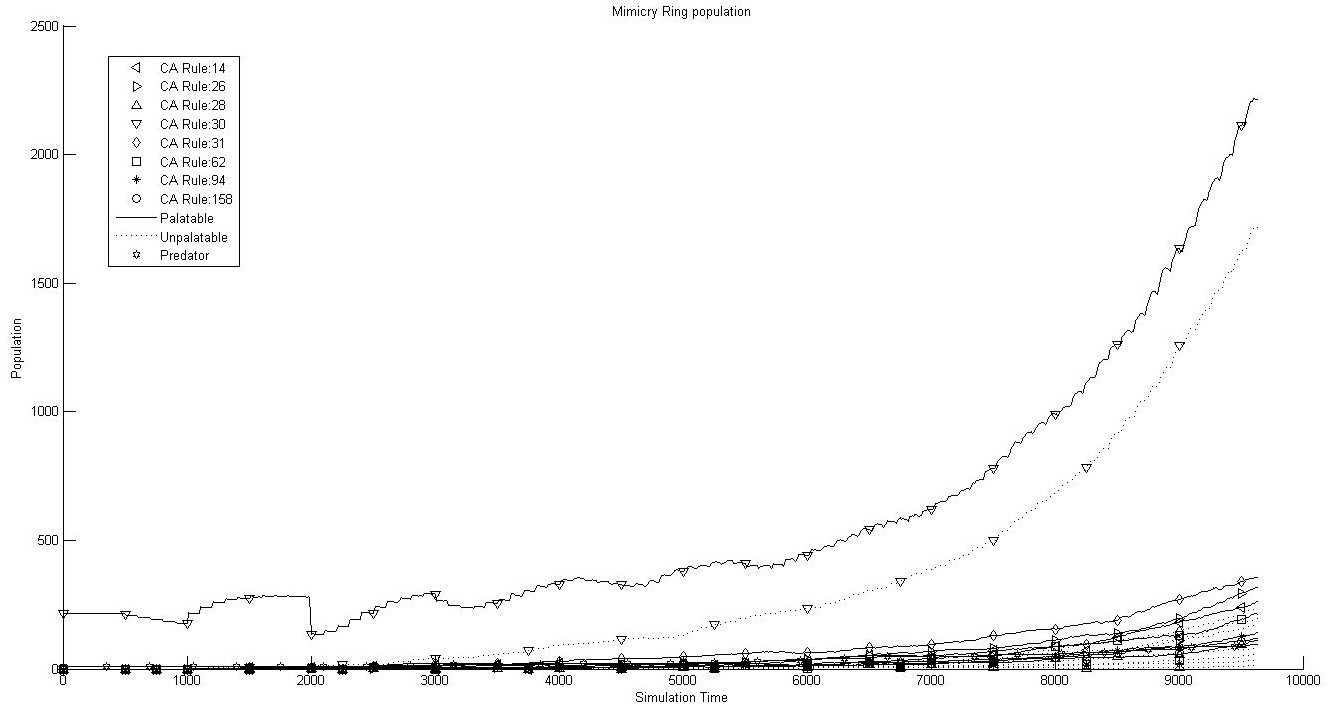
1 Prey species Unpalatable:



From unpalatable species we see a bunch of rings with majority of unpalatable species created.

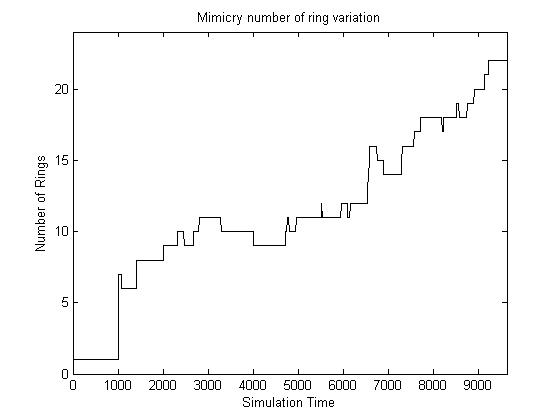


Palatable:



From Palatable population we see a bunch of palatable rings created.

Major difference is the total number of prey population created. For unpalatable species total population reaches above 12 thousand. But for palatable species total population reaches nearly above 5000.



Initial configuration with predator motion slower than prey.

Initial configuration with prey population slower than predator.

Initial configuration with larger resolution of the prey CA pattern.

Increasing CA pattern diversity by changing pattern mutation rate.

initialize with a set of prey species with random patterns and then evolve with predator to observe the result.

Initialize predator decision to consume and not consume a prey species depending on palatability.

Initialize with same species of palatable and unpalatable ones and run the simulation. (should not take much effect to produce mimicry, can only establish that mimicry is sustainable).

No predator evolution(Same set of predators existing the entire population.)

# Application for the evolution of mimicry

Part of this thesis was to think about whether the evolution of mimicry can be used in a problem solving scenario similar to evolutionary programming or genetic algorithm as it is used to optimize solutions using mathematical functions. Predator-prey co-evolution has also been used for solving interesting problems (Hillis, 190), giving better result than conventional methodologies.

The biggest challenge faced while searching for the appropriate problem to be optimized is the idea of associating palatability with CA pattern with which the prey species has been represented. If we consider the CA pattern to be a certain solution to a problem then the set of 2D CA pattern among which the prey species vary could be considered as the solution set of the problem. And if we consider that the predator species are responsible for selecting the appropriate pattern based on their palatability, then we can consider palatability as the criteria for selection of the pattern (or the evaluation/fitness function for the case of Evolutionary Programming/Genetic Algorithm).

If the predator associates the CA pattern with palatability then it does not make any sense of having a **mimic** in the solution space as mimics will have the same pattern with opposite palatability. So using the evolution of mimicry to solve an optimization problem is futile if we try conventional problems which already can be solved with the help of evolutionary programming or genetic algorithm.

So the kind of problems we should be looking for applying the evolution of mimicry, are the ones which cannot be solved with conventional evolutionary methods. We should be looking for a problem where the idea of deception can be useful in term of solving it. Unfortunately during the time of this research we were unable to find such a problem.

# Conclusion

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